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MAGNETIC ENHANCEMENT OF THE IONIZED LINES
OF THORIUM INVOLVING THE MECHANISM OF
AMBIPOLAR DIFFUSION

BY



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A THESIS

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DEPARTMENT OF PHYSICS

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THE UNIVERSITY OF ALBERTA
FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled MAGNETIC ENHANCEMENT OF THE IONIZED LINES OF THORIUM INVOLVING THE MECHANISM OF AMBIPOLAR DIFFUSION, submitted by P.H.L. Pang in partial fulfilment of the requirements for the degree of Master of Science.

Date

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ABSTRACT

The magnetic enhancement effect on thorium spectrum lines emitted from various ionization stages, and excited in an interrupted vacuum arc, has been investigated qualitatively and quantitatively in view of its explanation based on the concept of ambipolar diffusion.

Photographs, showing clearly the different enhanced degree on the ionized lines in the different fields, were obtained. Intensity measurements accurate to $\pm 20\%$ or better were made on four of the identified thorium lines coming from different ionization stages.

The experimental results obtained agree fairly well with the theory in that the enhancement effect appeared to be approximately proportional to the square of the magnetic field and to the inverse of the pressure. It also indicated an approximate proportionality to the square of the ionization stage of the spectral lines.

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CHAPTER I

INTRODUCTION

"MAGNETIC ENHANCEMENT" is the phenomenon attributed to the "intensifying" or "enhancing" effect of a magnetic field on the spectral line intensities due to ionized atoms. One form or other of this phenomenon is found to occur for many elements and light sources. In contrast, it is also observed that a magnetic field weakens lines of neutral atoms as in the case of the lanthanides when the light source is an electric arc.

One use of this phenomenon, first made by Klinkenberg,¹ is that of assigning lines in atomic spectra. In a paper published in 1950, he pointed out how the spectra of Th I, II, III and IV may be systematically distinguished by measuring their relative intensities in successively increasing fields. His observations showed that the enhancement is stronger for the line whose degree of ionization is higher. In an analogous way Anderson,² after investigating the effect on scandium and lutetium, assigned several lines to Lu II which had previously been assigned to Lu I.

Magnetic Enhancement in astrophysics is discussed by Babcock³ in his analysis of the spectra of some

A-type stars. However, in this case, the stellar lines intensified are those that occur in absorption and are saturated, i.e., on the nearly horizontal part of the curve of growth. The intensification which also depends on the strength and direction of the magnetic field over the surface of the star is found to be more pronounced for those lines which have wide multi-component Zeeman patterns.

Babcock showed that for a sufficiently strong magnetic field and in the absence of turbulence the intensification factor will have an upper bound given by

$$\left(\frac{W_1}{W_0} \right)_{\max} \rightarrow \left(\frac{n}{2} \right)$$

where W_0 , W_1 are the equivalent widths of the line without and with a field, respectively, and n is the number of Zeeman components.

Experimental data from Struve and Swings' observations⁴ on the A-type stars show satisfactory correspondence to the above suggestion.

The actual importance of the magnetic enhancement effect in the A-type stars lies in the fact that there is now no more doubt about the existence of a magnetic field in their atmospheres, and an explanation has been found for anomalies in their spectrum line intensities, which had remained a mystery for many years.

Results from various investigations into the effect have been discussed by Pinnington,^{5,6,7} who pointed out the dependence of the degree of enhancement on (a) the light source and (b) the element.

For the light source, it is found that if the same element is used with different light sources and in the same magnetic fields, the resulting intensification of a particular line will be different. Thus, the spectra of neutral atoms of lutetium⁵ and erbium⁸ are found to be affected by a magnetic field to a much higher degree while using an arc source than from a microwave electrodeless tube source. There is also an interdependence on the variable parameters of the light source involved, such as the voltage supplied to the arc source or the external inductance in the mercury source used by Raoult in 1949.⁹ All these facts suggest an explanation of the phenomenon related to some external mechanisms rather than to the properties of the element alone.

As for the case involving a dependence of the magnetic enhancement on the element used, Pinnington stressed that the enhancement is more pronounced in rare earths than in any other group, as is demonstrated by the reports on lutetium⁵ and ytterbium.¹⁰ He then pointed out that these elements are known to have several terms lying close enough to the ground state to be considered as densely

populated at modest temperatures, so that their principal lines are all optically thick: "of all the lines listed by Corliss and Bozman (1962) for spectra of neutral atoms of the lanthanide and actinide series of elements (i.e., the two series of rare earths), over 70% have their lower level within $10,000 \text{ cm}^{-1}$ of the ground state, whereas the corresponding average for all other elements is below 40%".⁷ This suggests that the enhancement of the spectral lines is related in some way to their optical thickness.

The theme of this present project is an attempt towards a better understanding of the main causes of magnetic enhancement which, as suggested above, apparently involve both some external mechanisms and some inherent properties of the elements. However, the experiments to be reported here will be mainly concerned with the external mechanisms.

It was decided to base the experimental work on the interrupted arc, such as was used with thorium by Klinkenberg.¹ A full description of its construction is given in Chapter II of this thesis. The advantage of this source is that it acts as a source of ionized plasma in a region for which both the pressure and the magnetic field can be varied independently. Another reason for using this source was to test if the effects found by Klinkenberg for thorium also occurred for other spectra, since such a

source could be of great value in the analysis of poorly understood spectra.

The theory involved is suggested by Pinnington in his paper published in 1965.⁶ It concerns the restrained motions of the main plasma components, i.e., the ions, electrons and neutrals, that are discharged by the arc source in a magnetic field. It supersedes the previous explanations of the phenomenon put forward by Klinkenberg, who attributed it to the confinement of the ions,¹ and by Raoult involving electron confinement.⁹ Pinnington bases his theory on a collective behaviour of the plasmas, known as "Ambipolar Diffusion". This takes place in the arc in the following way: One of the two electrodes in the arc source vibrates to and from the other one, thus creating an interrupted luminous source of a fairly high temperature. In the partially ionized source of plasma so produced, the neutrals will drift towards the walls, unaffected by the electrons, ions or magnetic field. The electrons, because of their lighter mass, will diffuse much more rapidly than either the ions or the neutrals. As a result of the higher mobility of the electrons with respect to the ions a charge separation is created and this, in turn, will set up an electric field. The force exerted by the latter will be in such a way as to augment the drift velocity of the ions and retard that of the electrons.

Finally a state of balance is reached whereby both the ions and the electrons will be diffusing with the same diffusion constant, known as the Ambipolar Diffusion Coefficient.

Calculations and further discussions on the concept are described in Chapter III. The derivations from Pinnington's work⁶ show that, in the presence of a magnetic field and for a fairly low pressure the motions of the ionized plasmas are related in the following way:

$$\frac{(D_a)_H}{D^+} = \frac{1 + n}{(1 + \beta n)(1 + \omega^2 \tau^2)} \quad \dots (1-1)$$

where $(D_a)_H$ is the Ambipolar Diffusion Coefficient in the presence of a magnetic field H,

D^+ is the Diffusion Coefficient of the ions,

n represents the n^{th} stage of ionization of the line considered,

τ is the mean collision time,

$\omega (= \frac{eH}{m})$ is the Larmor frequency,

$\beta = \frac{\lambda^+}{\lambda^-} \frac{m^-}{m^+}$ with λ^+ , m^+ and λ^- , m^- as the mean free path and the mass of the ions and the electrons, respectively.

Since the mean collision time (τ) is dependent on the mean free path (λ) and thus on the pressure (P), and the angular velocity (ω) is dependent on the magnetic field intensity (H), the value $\frac{(D_a)_H}{D^+}$ in equation (1-1) will

depend on three factors:

- i) the magnetic field intensity (H)
- ii) the pressure (P)
- iii) the ionization stage (n).

In this work the line intensities are studied with respect to these three variable parameters. The results of these measurements are given in Chapter IV.

In view of the fact that the magnetic enhancement may be correlated to an inherent property of the element, the elements that have been chosen for the investigations are as shown in Table 1-1.

Table 1-1. Elements chosen in the study of magnetic enhancement.

	Ti (Z=22) $4s^2 3d^2 \ ^3F_2$		
	Zr (Z=40) $5s^2 4d^2 \ ^3F_2$		
X	Hf (Z=72) $6s^2 5d^2 \ ^3F_2$	Ta (Z=73) $6s^2 5d^3 \ ^3F_{3/2}$	W (Z=74) $6s^2 5d^4 \ ^5D_2$
	Th (Z=90) $7s^2 6d^2 \ ^3F_2$		

This table shows that all the elements have an outer d-electron in their ground state electron configuration. The first four (Ti, Zr, Hf and Th) have the same ground state 3F_2 and their last d-electron has consecutive values of the principal quantum number n . As for Ta, W and Hf, their last d-electron has the same principal quantum number. Also W III, Ta II and Hf I have the same electronic configuration, as do W II and Ta I. These facts may be relevant to the phenomenon of magnetic enhancement as might be shown by the plottings between the intensity ratio I_H/I_O and the field H , for each of those elements. (For similar reasons to those mentioned above, Lu ($Z=71$) was proposed in the place of X in the table, but it was not commercially available in a form suitable for the interrupted arc.) However, owing to the limited time available for this project, the spectra of the chosen elements were only photographed in different magnetic fields, so that the enhancement that is visible on the plates was not measured quantitatively.

In addition, the line enhancement in a magnetic field for thorium has been measured photoelectrically with respect to the three previously-mentioned parameters (i.e., H , P and n). Thorium is the element which was investigated qualitatively by Klinkenberg.¹ Some of the doubly- and trebly-ionized lines of thorium as identified

by Klinkenberg have been used, therefore, as a guideline to the investigations about the magnetic enhancement phenomenon in this project. The results and analysis are given in the later chapters.

CHAPTER II

APPARATUS AND EXPERIMENTAL PROCEDURE

The experimental procedure followed in this investigation of the magnetic enhancement of ionized lines was divided into two main parts. The first part dealt with the photography and identification of the enhanced spectral lines, and the second part with the measurement of their intensity. The apparatus that was used consisted of the following basic components: a vacuum arc source, an electromagnet, a grating spectrograph, a spectrum plate comparator, a grating spectrometer, a photomultiplier, a digital voltmeter, a digital recorder and the optical system involved.

2.1 The vacuum arc source.

The vacuum arc source which acted as the light source was built in this laboratory following the design drawn up by Klinkenberg in his experiments on the subject.¹¹ The arc was designed in such a way that it would run parallel to the magnetic field lines. This was necessary because of the difficulty of operating arcs across a magnetic field. (A self-sustaining continuous-arc discharge was not suitable for this experiment because of

the heat accumulation that would have occurred.) The electrodes were designed such that one of them was made to vibrate to and fro by a small motor, thus creating an interrupted arc source of about 30 volts, with an almost negligible temperature change. The chamber, in which the arc was contained, was evacuable, and pressures as low as 0.1 torr could be obtained.

Figs. 2-1 and 2-2 illustrate the structure of the arc source. Fig. 2-1 illustrates the section perpendicular to the magnetic axis and Fig. 2-2 that section parallel to it. The major component was a rigid outer octagonal aluminium chamber which was made air-tight to the pole pieces by means of rubber rings, forming a solid unit (Fig. 2-5). In the outer surfaces of the octagon were cylindrical holes in which heavy aluminium plugs (Fig. 2-3) were set. The plugs were tightened onto rubber rings lubricated with vacuum grease. Three of these plugs had each a circular hole drilled in it and fitted with a 2 mm thick quartz window. One of these quartz windows was the optical outlet of the light source.

Two of the plugs carried electrodes (Fig. 2-1) which were terminated in a clamp. The cathode, shown on the R.H.S. of Fig. 2-1, was fitted with a suitably-formed tungsten tip, and served as the vibrating electrode. It oscillated about an axis perpendicular to the plane of

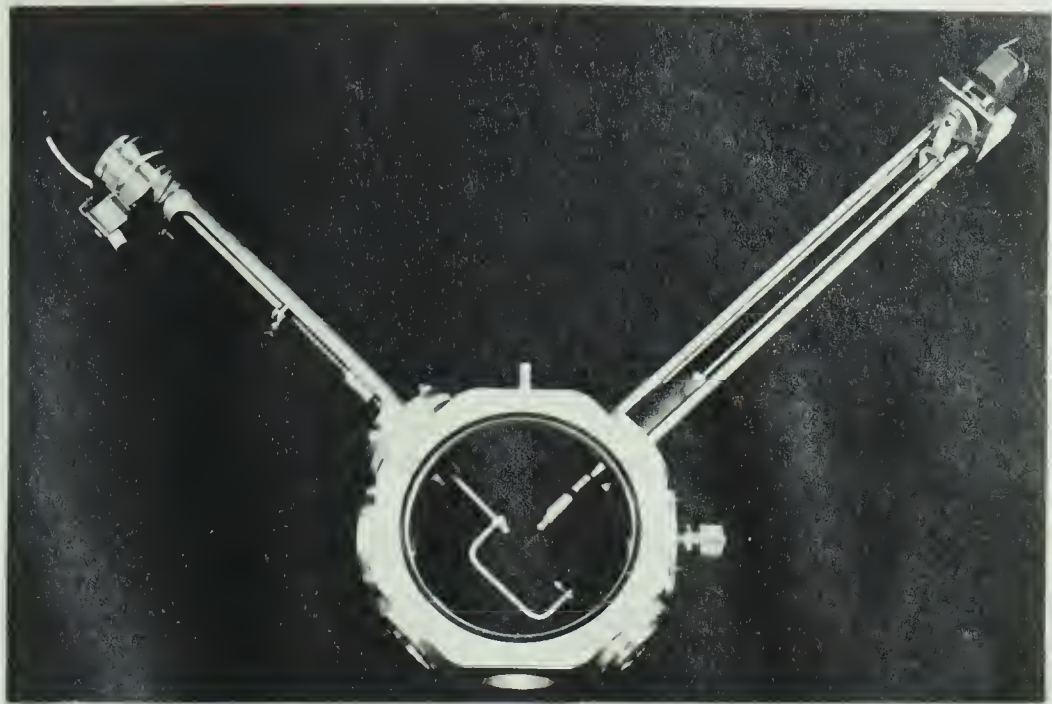


Fig. 2-1. Side view of Vacuum Arc Source.

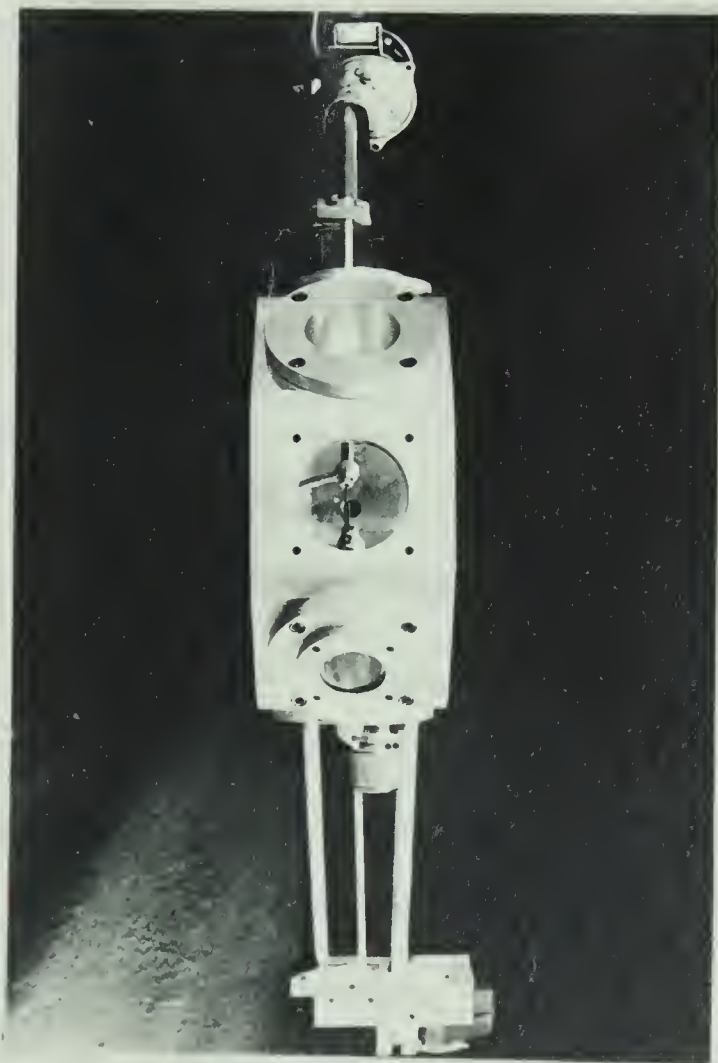


Fig. 2-2. Top view of Vacuum Arc Source.



Fig. 2-3.
Aluminium plug
with quartz
window.

the section shown in Fig. 2-2. To the rear or outside end of this electrode was fitted a small rectangular piece of aluminium. This aluminium piece could be slid to different positions yielding the appropriate oscillating amplitude of the electrode. At the same end of the electrode, adjacent to the aluminium piece, there was another sliding mechanism which could be adjusted until contact between the electrodes was obtained. (Contact was indicated by the sudden rise of the needle on the ammeter which was built into the power supply of the other electrode). The two adjustable mechanisms at the rear end of the "tungsten electrode" determined the gap that was allowed between the electrodes and thus the size of the arc's positive column. However, the gap between the electrodes diminished in size when the oscillations had been on for a certain while. That was because the fitting of the tungsten electrode through the aluminium plug, which was set up by means of a rubber tubing, was not a rigid one. Fortunately, that decrease usually occurred after every 10 to 15 measurements. To rectify this, the electrode through the rubber tubing was manually twisted back to its original position after every 4 measurements.

The anode, shown on the L.H.S. of Fig. 2-1, was fitted with the element (usually in the form of a rod)

whose spectrum was required. This electrode was fitted with a device such that it could rotate and/or just slide very slowly along its length. This was done to prevent "burning" of one spot on the element rod and to reduce the chance of oxidation, especially at higher pressure in the chamber. The speed of this sliding motion of the electrode was approximately 1.5 inches in 2 hours. The operating conditions of the arc were 15 to 50 volts and 1.5 to 4 amperes, depending mainly on the adjustment of the electrodes.

2.2 (a) The Electromagnet.

The electromagnet (Fig. 2-4) was a model 12C-AT-LI from Pacific Electric Motor Co., Oakland, California. It was fitted with tapered pole caps, each of 1 inch diameter and separated from each other by a 1.25-inch gap. To prevent "back-arcing" between the electrodes and the pole caps the latter were each insulated with a thin piece of perspex of about the same size as the pole end. The perspex pieces which also acted as the walls of the arc source, had had their surfaces roughened and blackened, as otherwise they would have formed two parallel plane mirrors whose reflections would have introduced an uncertainty in the resulting measured intensities.

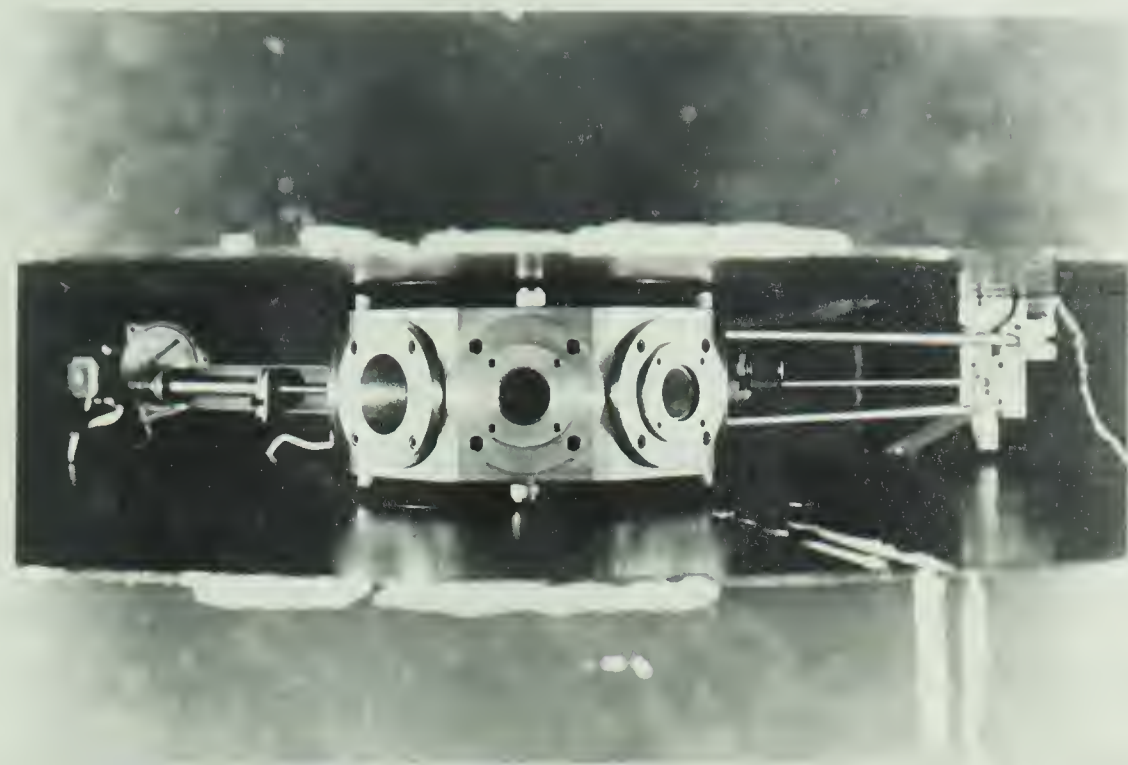


Fig. 2-5. Vacuum Arc Source forming a solid unit with poles of electromagnet.

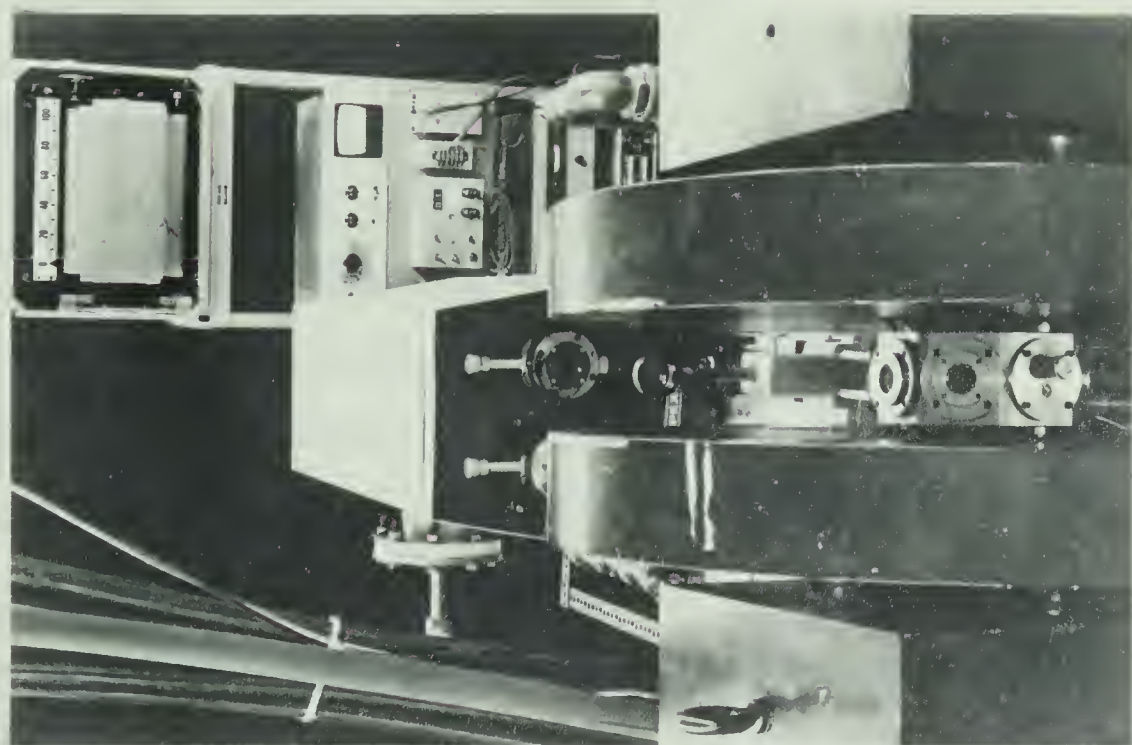


Fig. 2-4. Electromagnet, Spectrometer and Vacuum Arc Source.

When the magnet was operated at about half power (i.e., about 750 amperes) the field obtained was about 27 kilogauss with a power dissipation of 20 Kw. At full power (40 Kw) the field obtained was 30 kilogauss, i.e., only approximately 9% higher than the field obtained at half power. (This was because of the smallness of the tapered ends of the pole pieces, whereby magnetic saturation was already reached at half power.) Consequently the magnet was operated at half power to avoid overheating the magnet coils and the power supply. The coils were internally water-cooled at 7.2 G.P.M., 60 psi pressure drop, with a maximum allowed temperature rise of 40°C .

The mounting of the magnet was such that it could be rotated, raised or lowered, thus permitting a horizontal beam to be directed into the spectrometer described later.

(b) Calibration of the magnetic field intensity.

The magnet described above was suited to many studies, especially the Zeeman effect and magnetic enhancement. However, the intensity of the magnetic field obtained from the magnet was indicated approximately only by an ammeter which was built into the power supply. The scale on the ammeter ran from 0 to 1500 amperes divided at intervals of 200 amperes and was not linearly

proportional to the field intensity. It was therefore necessary to calibrate the field as a function of the applied voltage as is described below.

A digital voltmeter was connected to the magnet power supply to measure the voltage drops across a resistive section of the magnet coil circuit. A gaussmeter was then inserted between the poles and the field intensity registered for various values of the power supplied until the gaussmeter attained the maximum value of 30 kilogauss. A curve was then plotted between the voltage readings on the digital voltmeter and the corresponding field intensities on the gaussmeter. Using this curve any field intensity could then be obtained from the corresponding voltage reading.

The field supplied was not stable owing to the change in voltage of the magnet coils whose resistance was affected by their rise in temperature during operation. Stability was, however, recovered manually by turning the dial of the current supply until the reading on the voltmeter, that was connected for the field calibration, remained steady. Since this voltage was measured across a section of the coil circuit that did not change its resistance during operation, the current through the coils was maintained at a constant value, and hence the magnetic field was held constant in spite of

the change in resistance of the coil windings.

A further correction had to be applied to the magnetic field since it was necessary in this experiment to return the field to zero after having been run to its almost maximum values. This could not be accomplished simply by turning the current supply completely down since a "residual" field in the windings of the magnet power supply gave rise to a field of several hundreds of gauss, depending on how long the magnet had been running. To suppress this remnant field, an external circuit consisting of a battery, a switching key and a rheostat was connected in parallel with the current supply to the field coil windings of the magnet power supply to cancel the residual field there and hence reduce the current delivered by the supply to the magnet to zero.

2.3 The Grating Spectrograph and the Measurement of the Photographic Plates.

The photographs of the magnetically-enhanced spectral lines were taken with a 3.4 meter Ebert spectrograph. The latter was used with a 300 lines per mm blazed grating, ruled over a width of 14 cm. The grating was set at an angle of 4.8° , giving a spectrum range from about $2400 \text{ \AA}$ to $8000 \text{ \AA}$. The first order spectrum was isolated by using a glass filter which cut

out lines below $3500 \text{ \AA}$. In the first order the resolution power of the instrument was around 5×10^4 and the dispersion about $10 \text{ \AA/mm}$.

The spectra of Ti, Zr, Hf, Ta, W and Th were photographed using Kodak 103a-F plates. The plate-holder could be raised or lowered smoothly along the focal plane in the direction perpendicular to that of the slit so that spectra of the same element in different magnetic fields could all be obtained on the same plate.

The relative intensities at different field strengths had to be recorded for each line on each plate. This meant that not only the exposure time but also all the other factors that could affect the line intensities had to be kept constant for all exposures on a given plate. These factors involved essentially the adjustment of the power supplies for the arc source and the magnetic field, the pressure in the arc chamber and the length of the positive column. They usually varied during even short exposures, so that constant supervision over all of them was needed when the photographs were being taken.

Wavelength identifications of the spectra were based on thorium lines listed in Klinkenberg's work¹ and in the National Bureau of Standards Table of spectral line intensities.^{12, 13} Initial identifications of the wavelength regions appearing on the plate were made by comparing

with known lines of the mercury spectrum which was photographed at the same settings using a longer spectrograph entrance slit.

Photographs were taken at a grating angle of 4.8° , for which an accurate dispersion curve had been graphically plotted previously in this laboratory. The spectral lines were then accurately measured on a Zeiss Spectrogram Comparator. (The scale on the latter is in microns but was converted into Angstrom units by using the dispersion curve.)

2.4 The Spectrometer.

The spectrometer which was used to isolate those lines whose intensities were to be measured photoelectrically was a f/6.8 Model 1500, 0.75 meter in-plane Ebert type from Spex Industries. It was used with a grating having 1200 grooves per mm, and blazed for $5000 \text{ \AA}$. The first order dispersion was about $10 \text{ \AA/mm}$. Both its entrance and exit slits were used with a width of 300 microns, giving a resolution limit of about $3 \text{ \AA}$. Such a width was chosen so as to allow the complete passage of magnetically enhanced lines where the total broadening, mainly from its Zeeman effect, might amount to a width of about $2.5 \text{ \AA}$.

The spectrometer was fitted with a wavelength counter whose readings, accurate to $\pm 1 \text{ \AA}$, could be altered

either manually or automatically by a marker with a speed control. The counter was also initially calibrated by using a mercury lamp. In order to centre each line of the exit slit of the spectrometer, the signal from the photomultiplier fitted to the exit slit of the spectrometer was either displayed on a chart recorder or on a milli-microammeter. The wavelength scale was then adjusted until the output signal was a maximum for that particular line.

2.5 The Photomultiplier, Digital Voltmeter and Digital Recorder.

For the measurement of line intensities the photoelectric method was adopted. The principle involved in such a method involves direct conversion of the energy of the radiation into an electrical signal by means of a photomultiplier. This method could easily cover the visible spectrum range with a high "sensitivity", which is defined as the slope of the curve relating the output to the input radiant energy, and with a good "linearity", i.e., the output current being almost proportional to the input light intensity, as could be shown by the closeness with which the sensitivity curve approached a straight line.¹⁴

The photomultiplier that was chosen for the experiment was the Model 6256s from EMI. Its threshold

of detection was quite low at room temperature; actually it gave a dark current at room temperature of 0.5×10^{-9} ampere for a gain of 4×10^7 when the overall voltage supply was 1750 volts.

Because of the high dependence of the gain on the voltage supply (a voltage fluctuation of $x\%$ in an n -stage multiplier changes the amplification factor by about $nx\%$) the regulation and stability of the power supply was important. To test the stability of the power supply, the photomultiplier was exposed to a constant light source and a constant voltage was applied. No significant variation of the output current was obtained, proving the power supply to be satisfactory.

Besides the sensitivity and the linearity of the photomultiplier, its "threshold" of detection was an important factor. The threshold is defined as the radiant power needed by the photomultiplier to produce an electrical signal that was at least as large as the electrical noise generated inside the multiplier. Any smaller signal would be buried in the noise. This noise or photomultiplier "dark current" has a magnitude which depends on many factors, the main ones being:

- a) the emission of electrons from the photocathode under the thermionic effect
- b) the secondary electron emission at the dynodes

- c) background radiation in the laboratory
- d) the statistical fluctuations in the electron flow of the circuit.

The mean value of the fluctuating dark current would represent the threshold of detection of the photomultiplier so that the ratio of the least detectable signal to the noise was about unity. The background radiation, such as X-ray or neutron, could in principle introduce some noise to the photomultiplier which could be reduced by wrapping the photomultiplier with lead shielding. In practice this contribution was negligible in the present work. The noise due to the secondary emission of the electrons could be reduced by operating the voltage between the dynodes below the critical level, though at the expense of a lower gain. The thermionic current usually forms the major part of the dark current. It is a function of the photocathode temperature and obeys the Richardson-Dushman equation:

$$J = BT^2 e^{-\phi e / KT} \quad \dots (2-1)$$

where

- J = Current density
- B = 120 A/deg²/cm²
- T = Absolute temperature in °K
- K = Boltzmann constant
- φ = Work function of the cathode material
- e = Electron charge.

The exponential factor in equation (2-1) would indicate a fairly large decrease in the dark current in the cooling of the photocathode. The dark current in the 6256s used in this work could actually be reduced by a factor of 10 by cooling it with dry ice for 30 minutes.

Because of the relatively intense arc source used in this experiment, the light intensities measured could give signals whose ratio to those produced by the noise was as much as 5 to 1 for the weakest line. The intrinsic line intensities were obtained by subtracting the background noise level from the signal obtained for each line. The signal-to-noise ratio could be somewhat improved by operating the photomultiplier at voltages below those recommended by the manufacturers.

The amplified signals produced in the photomultiplier were transmitted through a digital voltmeter - Hewlett Packard - Model 3440 A - which was connected to an automatic digital recorder - Hewlett Packard - Model J74 562 A. The recorder was switched to the automatic setting that would register readings at one-second intervals. Several readings were taken for each intensity measurement. The average intensity value and the mean deviation, or percentage error from the statistical fluctuations involved, were calculated.

The large fluctuations in the voltmeter readings

which were due partly to the varying noise levels but mainly to the flickering nature of the light source, were quite a problem at the initial stage of the experiment. However, the problem was partially overcome by shunting the terminals of the voltmeter with a capacitor of 0.5 microfarad. This capacitor, being in series with the built-in high impedance of the digital voltmeter, formed a "low-pass" filter which smoothed the output signal over many cycles of the interrupted arc source.

2.6 The Optical System.

In connection with the optical arrangement (Fig. 2-6) set up for the experiment the following components were used:

For the first part, i.e., for the photography, a front-surfaced concave mirror (diameter 6", $f=60.5"$), supported by an adjustable bearing on the wall of the laboratory, was used to reflect the light from the vacuum arc source (emitted through the quartz window of its chamber) via a lens and a glass filter onto the spectrograph slit. The lens near the slit served to control the size of the image that was focused at the spectrograph slit. The image could not be made too small as the beam was always oscillating to and fro because of the uneven length of the positive column caused by the motions

of the electrodes and by the confinement of the plasma components in the magnetic field at the arc source. The glass filter was used to eliminate the second order lines when working in the $5000 \text{ \AA}$ - $6000 \text{ \AA}$ region.

For the second part, i.e., for the intensity measurements, the set up was the same except that the concave mirror was not used, the light being focused directly by a lens. The alignment of the optical components was undertaken by means of a small helium-neon laser. The laser was made to pass first through the exit slit, after having removed the photomultiplier that was fitted there, then through the entrance slit and a quartz lens onto the "contact" spot of the electrodes inside the vacuum arc chamber.

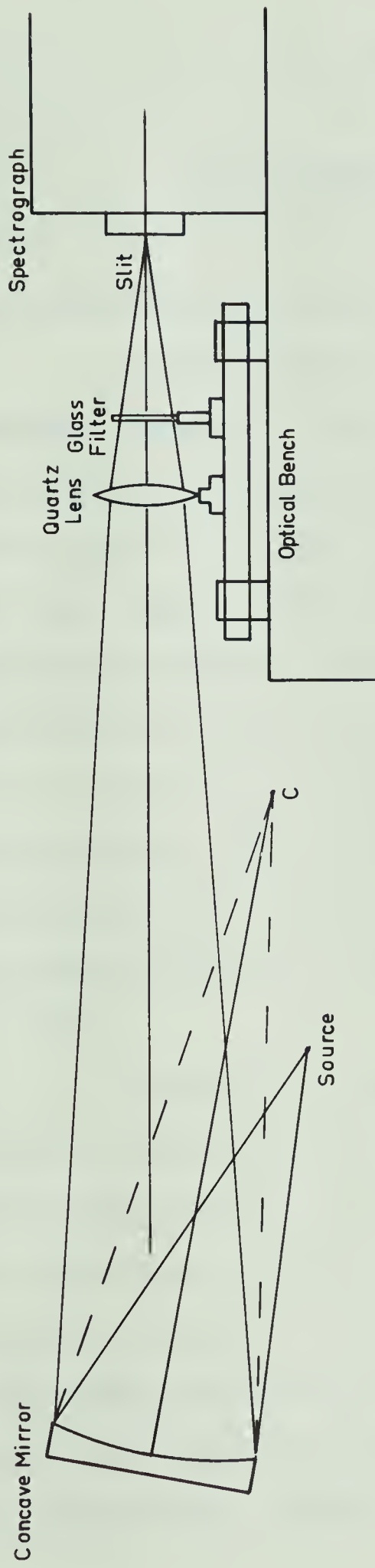


Fig. 2-6a Optical Arrangement for Photographing the Spectra

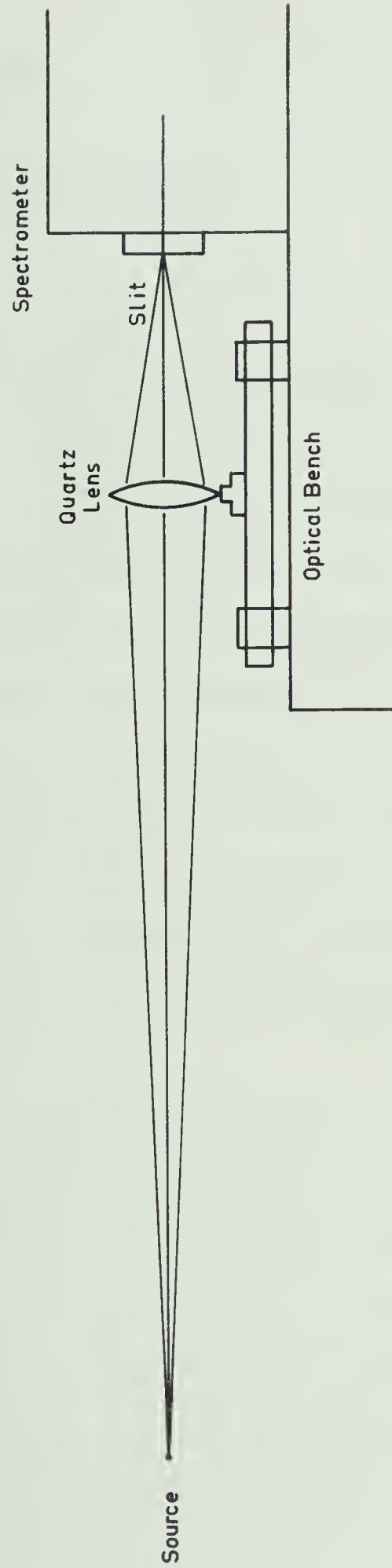


Fig. 2-6b Optical Arrangement for the Intensity Measurements

CHAPTER III

THE INTERRUPTED VACUUM ARC

3.1 Arc Definition and Characteristics.

Studies made on the electric arc are indeed numerous. However, a good part of what is now known on this topic has a purely empirical basis. The definition of the arc is in itself a problem since the same word has been used to describe several types of electrical discharges which may appear more or less the same but which differ in the physical mechanisms involved. In general the arc is defined in terms of its current and voltage drop. The current should exceed a threshold between 0.1 and 1 ampere, the upper limit to the applied potential difference lying between a few volts and tens of volts.

According to Hasler and Dietert¹⁵ an arc is defined as "that part of a discharge which starts about one millisecond after an electrode gap has been broken down and continues for the duration of the discharge, provided that the current is of the order of magnitude of amperes". They chose the time, one millisecond, because it takes about this length of time for a discharge to achieve thermal equilibrium. Before that time the discharge is in a

transition stage that starts with a spark and gradually converts to an arc. The definition fits well the interrupted d.c. arc used in this project, whereby the discharge was initially brought about by the spark induced by the electrode contact.

Arc discharges can be divided into two classes: "high-pressure arcs" and "low-pressure arcs". Their difference is indicated by firstly the temperatures T^+ , T^- and T_g of the three main plasma components (i.e., the ions, electrons and neutrals, respectively) and secondly the pressure of the arc. The temperatures are determined by the kinetic equation:

$$\frac{3}{2}kT = \frac{1}{2} m\bar{v}^2$$

The high-pressure arc is characterized by the fact that

$$T^+ \approx T^- \approx T_g$$

showing that the plasma is in a state of Local Thermodynamic Equilibrium. This type of arc is usually obtained when the pressure is about 100 torr or more.

As for the low-pressure arc,

$$T^- > T^+ \approx T_g$$

In this type of arc the electron temperature is usually higher than that of the heavy particles by a factor of 100 or so. This is because at low pressures the electron

mean free path is long enough for the electrons to gain appreciable energy from the electric field between collisions, whereas they lose little energy by elastic collisions with the heavy particles. The pressure range for this type of arc is between 0.01 and 6 torr. In addition, the low-pressure arcs can be divided into two sub-classes: (a) those in which the mean free path is greater than the tube radius; (b) those in which the mean free path is smaller than the tube radius. In the first case the theoretical calculations involved are based on the diffusion of the ions and in the second case the concept of ambipolar diffusion is applied.

There also exists an "intermediate-pressure arc" in which the pressure is between 6 and 100 torr. The collective behaviour of the plasma components in such an arc will be intermediate between those which characterize the high-pressure and the low-pressure arcs. In this type of arc the temperatures T^+ and T_g are equal, but lower than T^- by a factor of 10 to 15 instead of 100 or so as in a low-pressure arc.¹⁶ However, at a pressure of 10 torr (which was the pressure of the arc used by Klinkenberg¹ in his investigations of the magnetic enhancement of thorium lines) the arc can be approximated to a low-pressure one, **rather** than to a high-pressure one, since 10 torr is almost within the "low-pressure arc" range.

Also, since a pressure of 10 torr is higher than the generally accepted low-pressure range (1 to 6 torr) where the mean free path is much larger, it can therefore be concluded that, if the intermediate-pressure arc of about 10 torr were to be approximated to a low-pressure one, the mean free path in it could be considered as being smaller than the tube radius, so that the application of ambipolar diffusion to such an arc is justified.

3.2 Ambipolar Diffusion.

(a) Introduction

In a glow and low-pressure arc the average density of the charged particles can easily attain a value of the order of 10^{15} per c.c. At a density above 10^8 per c.c. the interaction between the charged particles cannot be ignored. The result of such an interaction, which is a fundamental property of plasmas, is their tendency to form a state of neutrality against external and internal influences. This result is confirmed by the two basic theories of Debye and Hückel¹⁷ and Tongs and Langmuir¹⁸ in which they introduced the well-known key parameters: the "screening length" and the "plasma frequency", respectively. From these theories it can be seen that plasma having "normal" parameters can exist in a non-neutral state only in relatively thin sheaths or on a relatively

short time scale. Consequently, in the bulk of the plasma and for usual values of the parameters the positively and the negatively charged particles have approximately the same density.

Schottky in 1924¹⁹ treated the above fact mathematically by considering a simple model of the positive column made up of electrons and of much heavier positive ions. He then introduced the concept of the Ambipolar Diffusion Coefficient, the value of which was determined to be equal to the average of the diffusion coefficients of both species, weighted by the inverse of the relevant mobilities. This theory is applied in most of the modern treatises on electrical discharges in gases and it certainly contributes much towards understanding them.

The problem was also tackled by Allis²⁰ who obtained some useful results by making the "quite rigid" assumptions of congruence and proportionality. However, this theory and that of Schottky, within the scope of their assumptions, are true only in the case of infinite, uniform, cylindrical positive columns. In the case of non-cylindrical columns of finite length some difficulties arise, as was pointed out by Hoyaux.²¹ In the latter's treatise he separated the radial ambipolar diffusion from the longitudinal drift, in which ions and electrons behave independently from each other. Actually Hoyaux's

method is a generalized form of Schottky's theory, flexible enough to be extended to non-cylindrical columns and columns of finite length.

Ambipolar diffusion is of a more complicated nature when a significant magnetic field is involved. In a magnetic field, the concepts of mobility and diffusion acquire a tensor nature, as was studied by Allis.²⁰ A generalization of Allis' theory was then attempted by Friedricks and Mastrup²² in which, besides the assumptions of congruence and proportionality introduced by Allis, and because of the rotational effects of the magnetic field, they made an additional assumption concerning the curls of the electron-and ion-particle fluxes. They then calculated the components of the ambipolar diffusion tensor. However, their equations led to incompatible results in some other cases.²³ Therefore, ambipolar diffusion in a magnetic field is still not a completely resolved problem.

(b) Basic Theories of Ambipolar Diffusion.

In the absence of the magnetic field, the drift velocity V of the plasma components produced in the electric arc can be related to either the external electric field E or the gradient of the concentration ∇N . In the first case the mobility μ is involved, and in the second

the diffusion coefficient D . These two basic relations are

$$V = \mu E \quad \dots (3-1)$$

$$V = -(D/N) \nabla N \quad \dots (3-2)$$

In the first case the drift results from mobility of the individual particles induced by the electric field, whereas in the second case the drift is the result of the particle diffusion between regions of different concentrations. However, it is well-known that both the diffusion and the mobility phenomena can be combined through the concept of "partial pressures" applied to the appropriate particles. In such a combination "Einstein's relation"

$$\frac{D}{\mu} = \frac{KT}{q} \quad \dots (3-3)$$

follows automatically.²⁴ Here K is Boltzmann's constant and T is the temperature of the appropriate particles with charge q . This relation, which has been experimentally confirmed, will be used more often in the later discussions of this topic.

The phenomena leading towards ambipolar diffusion are usually described as follows: A charge separation will tend to take place because under the same field electrons have higher velocities and also because the diffusion coefficient D^- of the electrons exceeds considerably that,

D^+ , of the ions. However, this charge separation can only exist to a significant extent over the space scale of the Debye screening length or during the time scale of the plasma oscillation; otherwise, the plasma has to stay quasi-neutral.

Once charge separation has occurred, an electric field will be generated between the electrons and the positive ions. This field will tend to retard electrons and accelerate the positive ions in order that both drift velocities are equal. In this state of ambipolar diffusion, as conceived by Schottky, the velocities of the species are given as follow:

$$V^+ = \mu^+ E - (D^+/N^+) \nabla N^+ \quad \dots (3-4)$$

$$V^- = -\mu^- E - (D^-/N^-) \nabla N^- \quad \dots (3-5)$$

In the scope of this procedure the charge separation required to balance the rates of flow is assumed to be negligible compared to the actual particle density. This assumption is justified, since, in practice, the charge separation, $N^+ - N^-$, is of the order of $10^5 - 10^6$ per c.c., whereas the actual particle density, $N = (N^+ + N^-)/2$, is of the order $10^{14} - 10^{15}$ per c.c. in low pressure arcs. Hence we may put

$$\begin{aligned} N^+ &= N^- = N \\ \nabla N^+ &= \nabla N^- = \nabla N \end{aligned}$$

Also, because of the steady conditions that exist,

$$V^+ = V^- = V$$

Equations (3-4) and (3-5) are then equated and E eliminated to give:

$$V = - \frac{D^- \mu^+ + D^+ \mu^-}{\mu^+ + \mu^-} \frac{1}{N} \nabla N$$

and, since

$$NV = \frac{\partial N}{\partial t}$$

$$\therefore \frac{\partial N}{\partial t} = - \frac{D^- \mu^+ + D^+ \mu^-}{\mu^+ + \mu^-} \nabla N$$

Comparison with the definition of the diffusion coefficient gives

$$\frac{\partial N}{\partial t} = - D_a \nabla N,$$

$$\text{where } D_a = \frac{D^- \mu^+ + D^+ \mu^-}{\mu^+ + \mu^-}$$

D_a is called the coefficient of ambipolar diffusion in which the particle polarity becomes immaterial.

If both species are at the same temperature as in high pressure arcs, $T^+ = T^- = T$. Then, from the Einstein relation (equation 3-3), which we assume to be applicable to both electrons and ions, we have

$$\frac{D^+}{\mu^+} = \frac{D^-}{\mu^-} = \frac{KT}{e}$$

and (3-6) becomes

$$D_a = \frac{2D^+ \mu^-}{\mu^- + \mu^+} \approx 2D^+ \quad \dots (3-7)$$

since $\mu^- \gg \mu^+$.

If the electron temperature is much higher than the ion temperature, then from (3-3)

$$\frac{D^-}{\mu^-} \gg \frac{D^+}{\mu^+}$$

$$\text{and } D_a \approx D^- \frac{\mu^+}{\mu^-} \approx \mu^+ \frac{KT^-}{e} \dots (3-8)$$

As was explained earlier, the problem of ambipolar diffusion in a magnetic field has not yet been solved. In the following section an attempt will be made to at least indicate which factors must be involved.

- (c) Ambipolar diffusion of the low-pressure **arc** in a longitudinal magnetic field.

The problem of ambipolar diffusion in a magnetic field, which prevails in the low-pressure arc when its positive column is sufficiently long with respect to its radius, is indeed a very complicated one as indicated in the mathematical treatments undertaken by previous workers.^{16, 20, 23, 25} In fact, no complete solution has been found yet. So far, more manageable calculations have been obtained by Hoyaux¹⁶ who corrected the ambipolar diffusion coefficient in the magnetic field in the second order. The value he obtained for the diffusion coefficient is exactly the same as that obtained by Townsend, Longmuir & Mott-Smith^{26, 27}, although his method is totally different since it involves the tensor nature of the product between

the mobility coefficient μ and the magnetic field H . The effective mobilities are taken as the ones which are perpendicular to the magnetic field, because the so-called "parallel mobilities" are unaltered by the field. In short, the corrected diffusion coefficient across the magnetic lines of force is as follows:

$$D_H = \frac{D_0}{1 + (\omega\tau)^2} = \frac{D_0}{1 + \left(\frac{\lambda}{r}\right)^2} \dots (3-9)$$

where $\omega(=\frac{qH}{m})$ is the Larmor frequency, τ is the mean time between collisions, λ is the mean free path and $r(=\frac{mv}{qH})$ is the Larmor radius for particles of mass m and charge q moving with velocity v perpendicular to a magnetic field H .

D_H may also be written in terms of the mobility μ , (defined in equation (3-1)) in the following way:

Suppose μ_1 is the initial velocity of a charged particle just after a collision and proceeds towards a terminal velocity μ_2 just before another collision.

Then the mean drift velocity V_d between collisions = $\frac{1}{2}(\mu_1 + \mu_2)$. (A better averaging would have been obtained if the true statistical velocity distribution were known but this modification is not important for the results to be discussed here.)

Assuming that at each collision the particle loses all its kinetic energy in the field direction, i.e., after collision it starts with a zero velocity component in the field direction,

then $\mu_1 = 0$.

Hence the mean drift velocity between collisions is

$$V_d = \frac{1}{2} \left(0 + \frac{qE}{m} \tau \right)$$

and comparing with equation (3-1):

$$\mu = \frac{1}{2} \frac{q\tau}{m}.$$

Since $\omega = \frac{qH}{m}$, the mobility is then denoted as $\mu = \frac{1}{2} \frac{\omega\tau}{H}$,

$$\text{so that } D_H = \frac{D_0}{1 + (2\mu H)^2} \quad \dots (3-9a)$$

Writing μ in terms of the mean free path gives

$$\mu = \frac{q\lambda}{2m\bar{V}_{TH}} \approx \frac{q\lambda}{2\sqrt{(3mKT)}} \quad \dots (3-10)$$

where $\bar{V}_{TH}$ is the mean thermal velocity.

In order to determine the magnitude of the effect described by equation (3-9) it is necessary to calculate $\omega\tau$ (or one of its equivalents). This may be achieved as follows:

$$\omega\tau = \frac{\lambda qH}{\sqrt{(3mKT)}} = \frac{qH}{N\sigma\sqrt{(3mKT)}}$$

where N is the particle density and σ the collision cross-section. Replacing N by its gas-kinetic value of $\frac{P}{T} \cdot 10^{19}$, where P is now in torr, yields

$$\omega\tau = \frac{qH\sqrt{T} \cdot 10^{-19}}{\sigma P \sqrt{3mK}} \quad \dots (3-11)$$

Assuming a typical cross-section for heavy atoms of 10^{-15} cm^2 then gives the following relations:

$$(\omega\tau)^+ = \frac{H\sqrt{T^+}}{\sqrt{M.P}} \times 0.611 \times 10^{-4} \quad \dots (3-11a)$$

for singly-charged ions of mass M a.m.u., and

$$(\omega\tau)^- = \frac{HT^+}{P\sqrt{T^-}} \times 0.261 \times 10^{-4} \quad \dots (3-11b)$$

for electrons. Equation (3-11b) makes allowance for the possibility that $T^- \neq T^+$ but is only an approximation as the collision cross-section has been taken as 10^{-15} cm^2 . This has been assumed since the electrons in the actual arc will collide mainly with the atoms and ions present. The values for $(\omega\tau)^-$ and $(\omega\tau)^+$ thus obtained indicate how the diffusion of electrons or ions will be affected by a magnetic field in the actual light source which is the subject of this thesis. The plasma consists of a mixture of atoms in various stages of ionization (both from the electrode material and from the gaseous atmosphere in which the arc burns) and electrons. The next step in this attempt to partially understand the behaviour of the interrupted vacuum arc in a magnetic field is to consider a mixture of neutral atoms, singly-ionized atoms and electrons, for which case the mechanism of ambipolar diffusion is applicable.

From equation (3-6), diffusion across a

magnetic field may be described by the relation

$$(D_a)_H = \frac{D_H^- \mu_H^+ + D_H^+ \mu_H^-}{\mu_H^+ + \mu_H^-} \dots (3-12)$$

where the subscript, H, indicates that the parameters are those in the presence of a magnetic field. These parameters are related to the field-free parameters and to each other by the following equations, in which it is assumed that the temperatures T^+ and T^- are unchanged by the magnetic field:

$$\mu_H^+ \text{ (or } D_H^+) = \frac{\mu^+ \text{ (or } D^+)}{1 + (\omega^+ \tau^+)^2} \dots (3-13a)$$

$$\mu_H^- \text{ (or } D_H^-) = \frac{\mu^- \text{ (or } D^-)}{1 + (\omega^- \tau^-)^2} \dots (3-13b)$$

$$\frac{\mu^+}{\mu^-} \approx \frac{m^- T^-}{m^+ T^+} \dots (3-13c)$$

$$\frac{D^+}{D^-} = \frac{\mu^+}{\mu^-} \frac{T^+}{T^-} \dots (3-13d)$$

Equations (3-11), (3-12) and (3-13), then yield the results shown in Table 3-1, for which the following values have been assumed:

$$M=200 \text{ a.m.u.}, T^+=5000^\circ \text{K}, H=3 \times 10^4 \text{ gauss.}$$

Table 3-1. Ambipolar diffusion in a magnetic field

P (torr)	T^-/T^+	$(\omega\tau)^-$	$(\omega\tau)^+$	$(D_a)_H/(D_a)_0$
0.1	100	5500	90	2.0×10^{-6}
1.0	50	780	9.0	1.4×10^{-4}
10.0	15	140	0.9	7.0×10^{-3}
100.0	1	55	0.1	0.2
1000.0	1	5.5	0.01	1.0

This calculation shows that the magnitude of the effect falls with increasing pressure, and is entirely unimportant in the high-pressure arc. It also shows that at 10 torr, the confining action of the magnetic field is restricted to the electrons, the motions of the ions being relatively unaffected. This is in agreement with the conclusions reached by Pinnington.⁶ Furthermore the dominant factor for pressures of 10 torr and less is $1 + (\omega^- \tau^-)^2 \approx (\omega^- \tau^-)^2 \propto H^2$. Thus the dependence of the diffusion coefficient should be as the inverse square of the magnetic field, and hence the intensity of the resulting spectrum lines (which will depend on the inverse of the diffusion coefficient across the magnetic field) might be expected to vary as the square of the magnetic field.

This calculation yields no information on the n -dependence (where n is the charge state) of the diffusion coefficient in a mixture of different ions as only singly-charged atoms were considered. Since the dominant factor was found to be $(\omega \tau)$, the values in Table 3-1 still approximately apply for a mixture of neutral atoms, n -fold ionized atoms and electrons. However the problem is more complex for a mixture of electrons, neutral atoms, singly-charged ions, doubly-charged ions etc. It might be linked more tightly with the electrons, but the exact dependence on n is difficult to forecast.

CHAPTER IV

RESULTS AND DISCUSSION

4.1 The Spectra.

The photographs of the line spectra of Ti, Zr, Hf, Ta, W and Th, at four different fields (0, 8.25, 23.25 and 27.45 kilogauss) and at a pressure of 0.2 torr, were obtained on Kodak 103a-F plates. On each of those plates the lines in the region 4900-6000 Å for the first order and 2450-3000 Å for the second order were investigated qualitatively with respect to their variation in intensity in the increasing magnetic field. The results obtained are summarized in Table 4-1.

Table 4-1. Observations of magnetically-enhanced lines on the photographic plates

Element	Total No. of Lines Observed	No. of Lines showing Weak Enhancement	No. of Lines showing Strong Enhancement
Ti	74	12	4
Zr	124	14	3
Hf	110	16	0
Ta	148	7	0
W	58	6	1
Th	93	15	4

Most of the lines which showed weak enhancement (i.e., those in the third column of Table 4-1) were identified as being those from the doubly-ionized atoms, as far as Zr, Hf and Th were concerned. (This is presumably the case for Ti, W and Ta for which a complete wavelength table including the lines from the second stage of ionization was not available.) As for those lines which showed strong enhancement (i.e., those in the fourth column of Table 4-1), they were identified as being from the trebly-ionized atoms on the thorium plate, and probably from atoms of the third or higher stage of ionization for Ti and Zr. The other lines, i.e., those which did not show any visible enhancement, were identified as being definitely from the neutral and singly-ionized atoms. It was also found that most of the lines which evinced the enhancement effect belong to the shorter wavelength region.

The lines Th I $4381.86 \text{ \AA}$, Th II $4094.75 \text{ \AA}$, Th III $5458.79 \text{ \AA}$ and Th IV $5420.38 \text{ \AA}$ were identified on the plate and were used in the qualitative and the quantitative investigations of the magnetic enhancement effect. Spectrograms showing these thorium lines are illustrated in Figs. 4-1a to 4-1d. It can be seen from these spectrograms that the effect on the Th I and Th II lines is hardly visible at any field, but that for Th III and Th IV lines is quite pronounced and does increase with the

H in KG

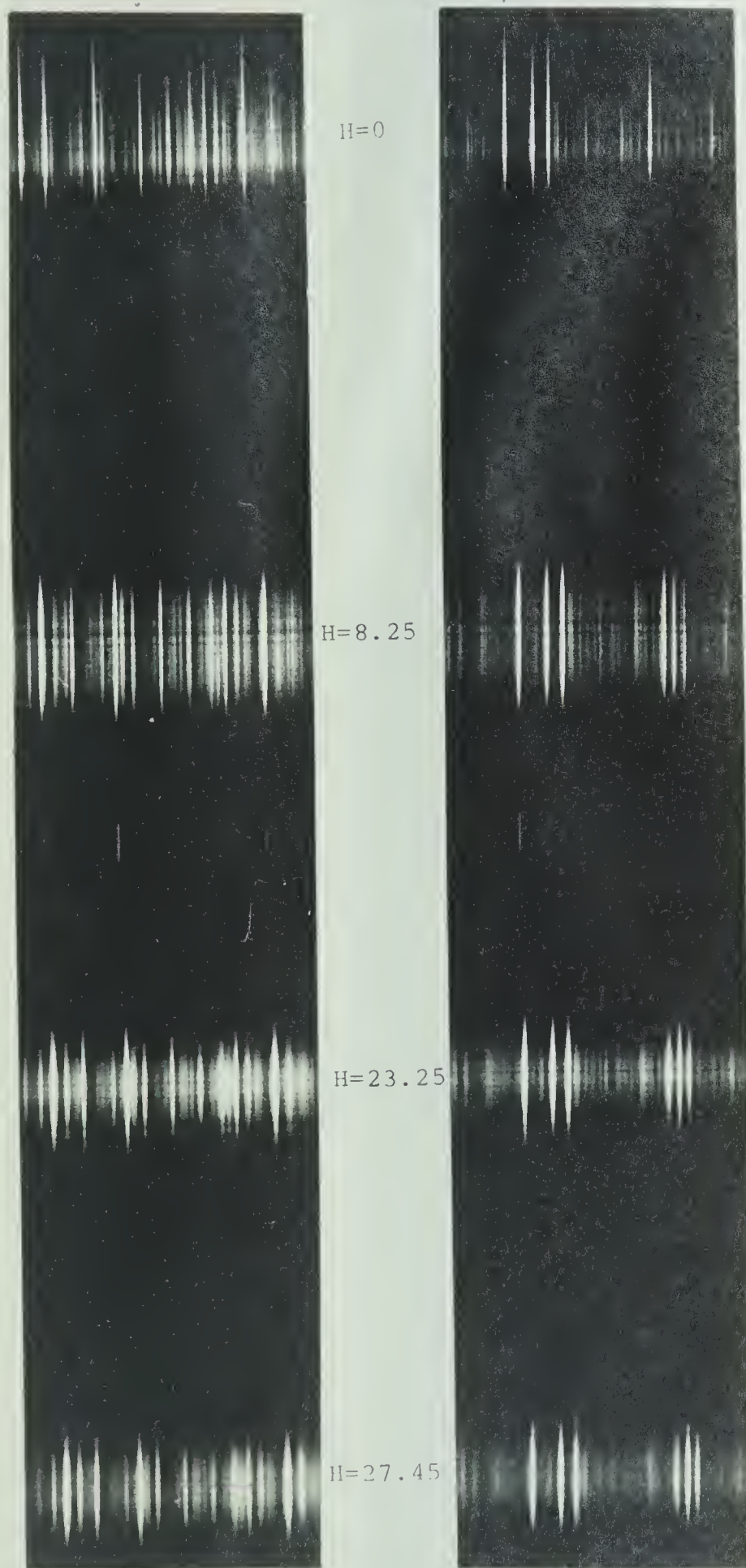


Fig. 4-1a&b. Magnetic Enhancement of ThII&I at $p=0.2$ torr.

ThII 4094.750

ThI 4381.900

Fig. 4-1c&d. Magneto-
Enhancement of ThIV&III
at $p=0.2$ torr.



ThIV $5420.38\text{\AA}$ ThIII $5458.79\text{\AA}$

magnetic field. This result is in agreement with that obtained by Klinkenberg¹ and is confirmed by the data shown in Table 4-2a. However, the photographs taken with the arc functioning at higher pressures showed a reduced effect on the Th III and Th IV lines, while that on the Th I and Th II lines remained the same. Hence, if magnetic enhancement were used for distinguishing Th III and Th IV lines from Th I and Th II, the optimum pressure to be used would be 0.2 torr, with a field between 20 and 27 kilogauss.

4.2 The Line Intensities and their Relationship to the Ambipolar Diffusion Coefficients.

The greatest problem in this work was encountered in the measurement of the thorium line intensities from the interrupted light source. Large fluctuations in the intensity readings were often recorded on the digital voltmeter, so that the mean deviation for each set of readings was quite high, as indicated in tables 4-2a to 4-2d and by the tall error flags in the curves shown in Figs. 4-2a to 4-2d.

In these tables, the line intensity measured at a field H is denoted by I_H and that at zero field by I_0 . The ratio I_H/I_0 , therefore, gives the magnitude of the enhancement factor at the field H . The data show

that the enhancement effect does indeed increase with the field, and to a stronger degree for thorium lines whose stage of ionization is higher, except for the neutral line for which a slightly weakening effect is indicated. The results shown in Table 4-2a are, in fact, a quantitative interpretation of those visualized on the photographs shown in Figs. 4-1a to 4-1d.

Using the data from Tables 4-2a to 4-2d, graphs of (I_H/I_0) as the ordinate against H as the abscissa were plotted, and the results are illustrated in Figs. 4-2a to 4-2d. It can be seen that the shapes of the curves so obtained are approximately what is to be expected, i.e., parabolic ($I_H/I_0 \propto H^2$) with the values of the ordinate, I_H/I_0 , always increasing from unity with a steeper slope for the lines whose degree of ionization is higher. However, the observed intensification effect varies much less rapidly with pressure than was forecast by the theoretical derivations, (whereby the intensification effect $\propto \frac{H^2}{p^2}$). An explanation for this will now be given.

Table 4-2. Values of the intensity ratio I_H/I_0 of thorium lines of different ionization stages at the corresponding magnetic field intensity H .

(a) For $P=0.2$ torr:

H in KG	I_H/I_0			
	$\frac{(Th\ IV)_H}{(Th\ IV)_{H=0}}$	$\frac{(Th\ III)_H}{(Th\ III)_{H=0}}$	$\frac{(Th\ II)_H}{(Th\ II)_{H=0}}$	$\frac{(Th\ I)_H}{(Th\ I)_{H=0}}$
0	1.00±16%	1.00±20%	1.00±20%	1.00±10%
8.25	2.46±17%	2.08±19%	1.02±16%	0.86±12%
16.45	4.53±18%	3.64±18%	1.21±16%	0.86±12%
23.25	6.40±15%	4.34±20%	1.18±15%	0.85±12%
27.45	8.78±12%	5.53±18%	1.24±18%	0.75±12%

(b) For $P=1$ torr:

0	1.00±16%	1.00±18%	1.00±20%	1.00±18%
8.25	1.83±25%	1.47±16%	1.09±20%	0.92±23%
16.45	2.93±15%	2.16±19%	1.11±21%	0.91±21%
23.25	3.65±17%	3.14±22%	1.18±21%	0.94±14%
27.45	4.73±21%	3.96±15%	1.25±23%	0.93±21%

(c) For P=5 torr:

H in KG	I_H/I_0			
	$\frac{(Th\ IV)_H}{(Th\ IV)_{H=0}}$	$\frac{(Th\ III)_H}{(Th\ III)_{H=0}}$	$\frac{(Th\ II)_H}{(Th\ II)_{H=0}}$	$\frac{(Th\ I)_H}{(Th\ I)_{H=0}}$
0	1.00±18%	1.00±20%	1.00±22%	1.00±18%
8.25	1.48±17%	1.22±18%	1.07±20%	0.94±14%
16.45	2.30±20%	1.51±21%	1.10±16%	0.95±14%
23.25	3.12±19%	1.87±19%	1.15±20%	0.93±15%
27.45	4.40±19%	2.34±19%	1.19±18%	0.95±18%

(d) For P=10 torr:

0	1.00±24%	1.00±20%	1.00±17%	1.00±18%
8.25	1.56±24%	1.22±18%	1.03±20%	0.95±12%
16.45	2.13±20%	1.51±13%	1.07±16%	0.93±17%
23.25	2.69±22%	1.83±16%	1.10±14%	0.96±18%
27.45	3.27±21%	2.05±14%	1.16±19%	0.93±18%

Fig. 4-2a. Graphs showing the relationship between the intensity ratios I_H/I_0 of ThI-IV and the fields H at a pressure $P=0.2$ torr.

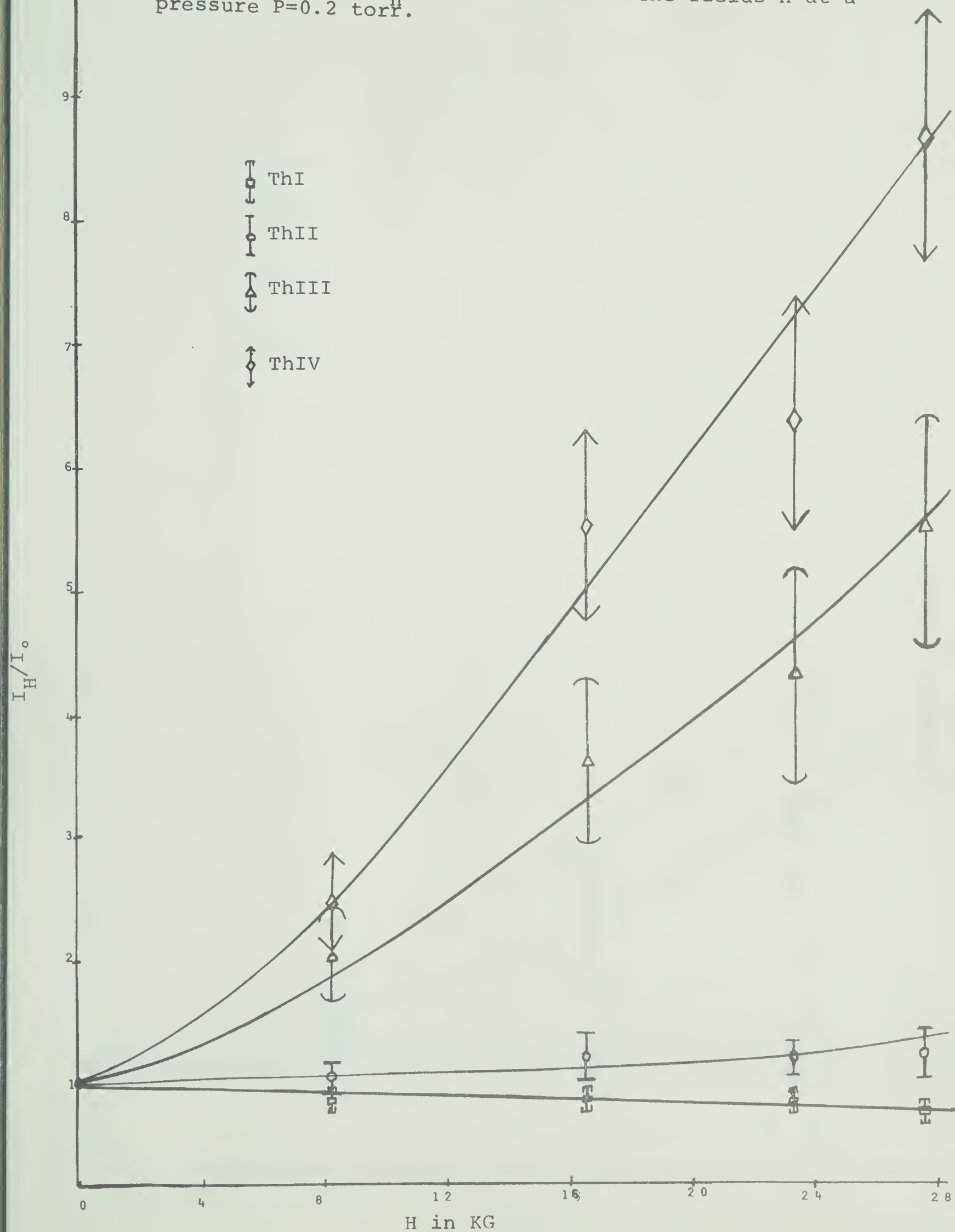


Fig. 4-2b. For P=1 torr

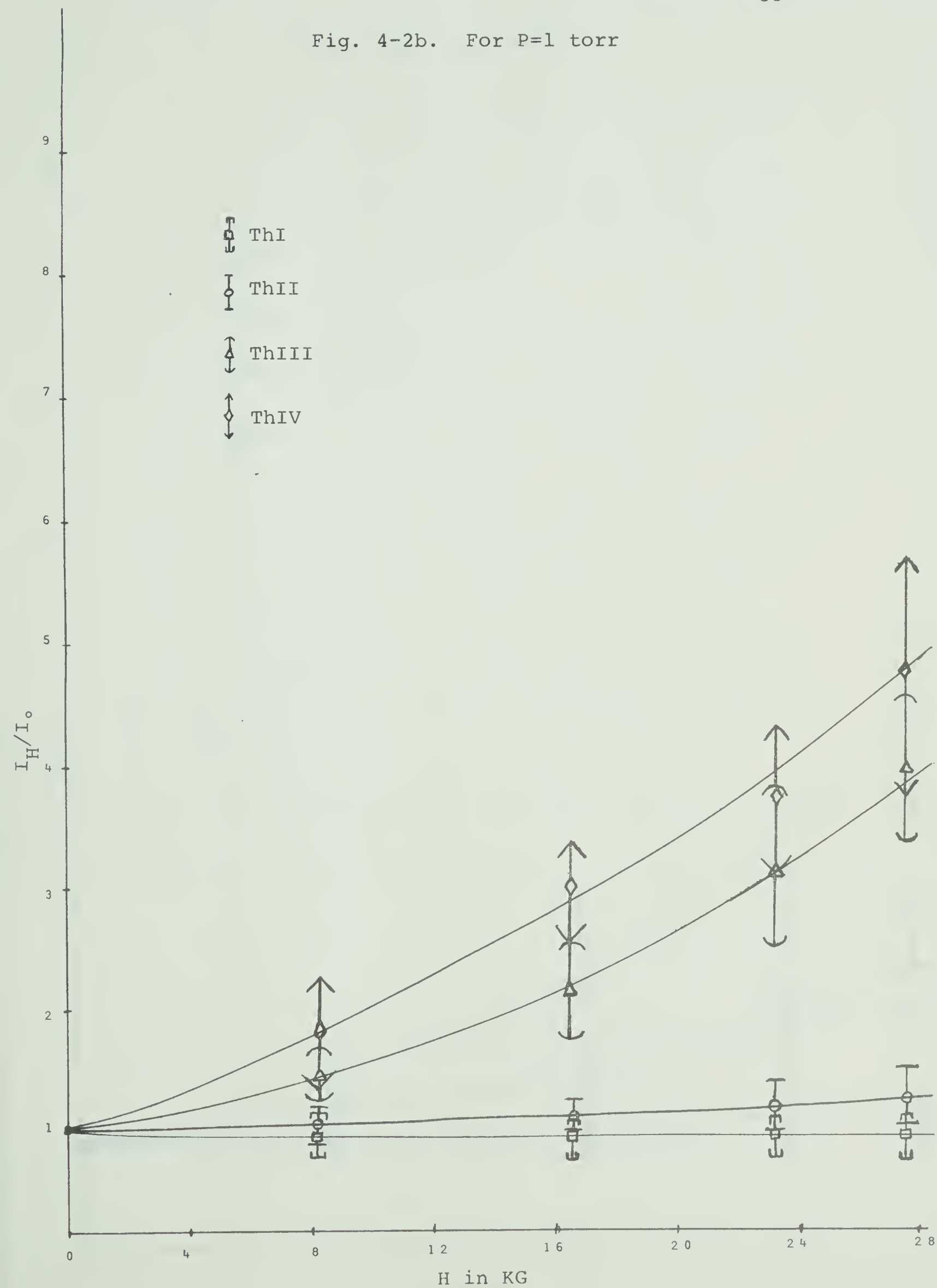


Fig. 4-2c. For P=5 torr

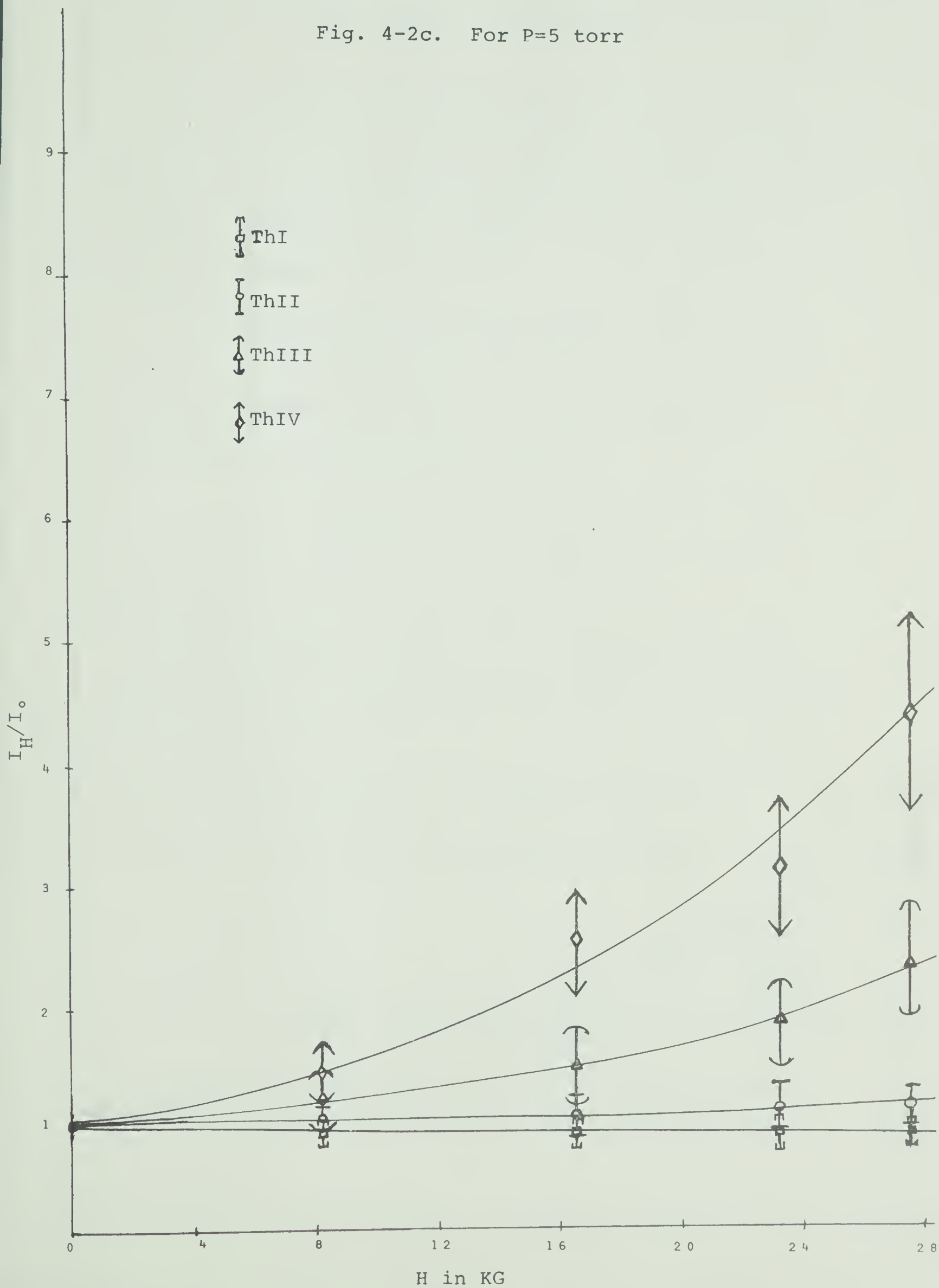
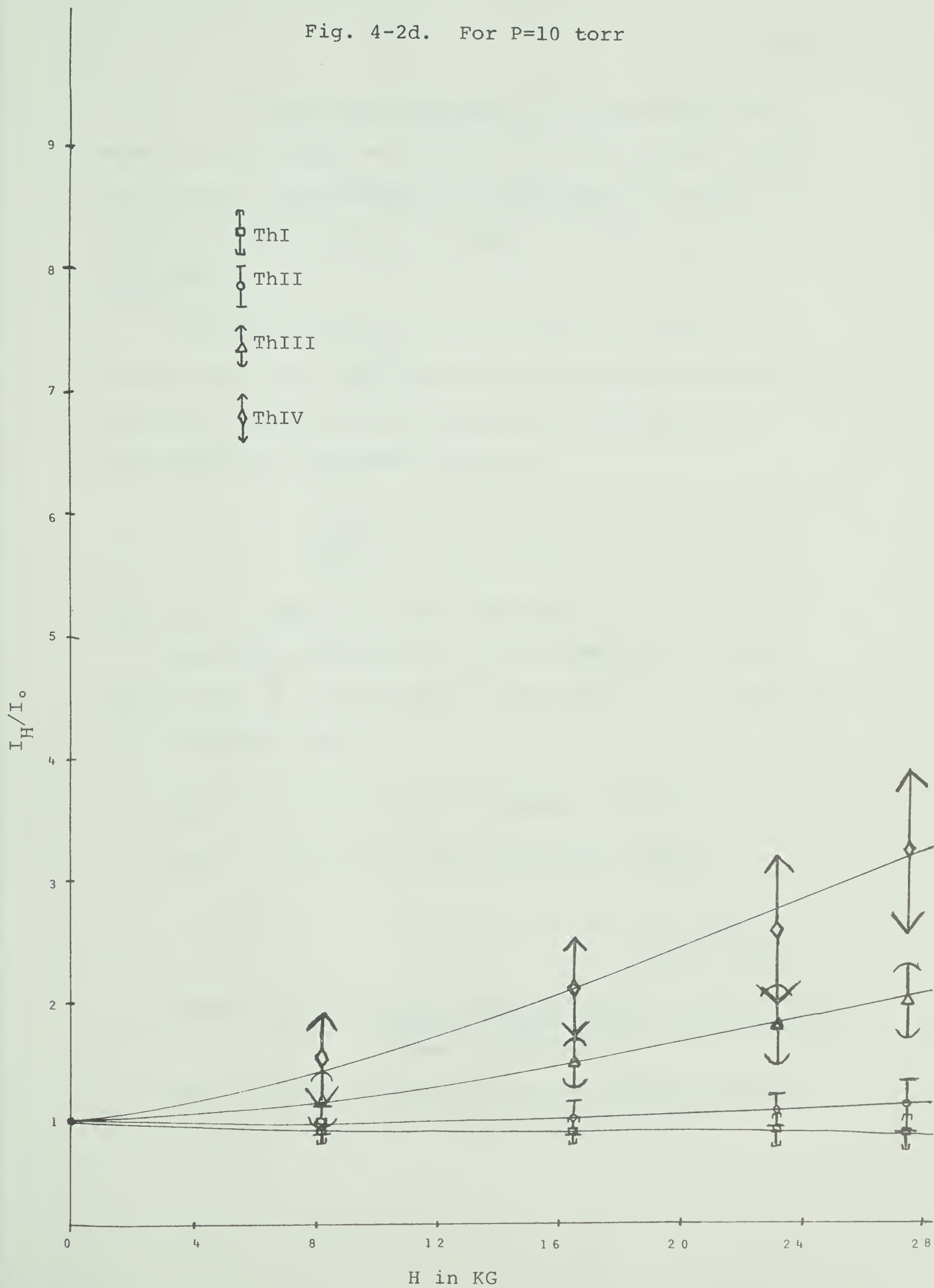


Fig. 4-2d. For P=10 torr



It was suggested earlier in this thesis that magnetic enhancement as found in the interrupted vacuum arc involves the phenomenon of ambipolar diffusion. A relation is therefore to be expected between I_H/I_0 and $(D_a)_H/(D_a)_0$:

From the theoretical calculations in Chapter III, it was shown that the diffusion in the magnetic field is primarily limited by the electron-field interaction governed by the following relation:

$$\frac{(D_a)_H}{(D_a)_0} = \frac{1}{1 + (\omega^- \tau^-)^2}$$

where $(\omega^- \tau^-)$ applies to the electrons.

Since the intensity will be in some way inversely proportional to the diffusion coefficient, it is therefore to be expected that:

$$\frac{I_H}{I_0} \propto 1 + (\omega^- \tau^-)^2 = 1 + \text{constant} \cdot H^2 (\lambda^-)^2$$

$$\text{where } \lambda^- = \text{m.f.p. of the electrons} = \frac{1}{\sum N_i \sigma_i}$$

$$= \frac{1}{N_g \sigma_g + N_{Th} \sigma_{Th}}$$

where σ_g, σ_{Th} = total cross-sections for collisions between electrons and gas or thorium atoms, respectively

and N_g, N_{Th} = number of gas or thorium atoms per unit volume respectively.

$N_g \propto P_g$, the partial pressure exerted by the gas atoms.

$N_{Th} \propto P_{Th}$, the partial pressure exerted by the thorium atom.

Then, $\left(\frac{I_H}{I_o}\right)$ varies as $1 + \alpha H^2$

where $\alpha \approx \left(\frac{1}{PA+B}\right)^2$,

$$P \approx P_g + P_{Th}$$

and A, B are constants.

The constants, A and B, can be solved from the observations. For instance, from the data obtained on Th III and Th IV at the maximum field (the statistics are too poor for Th II), Table 4-3 is first obtained. From this table any two equations involving $\frac{1}{AP+B}$ are equated to the corresponding observed value of I_H/I_o and solved for A and B. In this case, those denoted by * in Table 4-3 were chosen. Using the values of A and B thus obtained, the other values of $\sqrt{\frac{I_H}{I_o} - 1}$ are calculated. As the results show in Table 4-3, there is indeed a general agreement between the observed and the calculated values within the 20% spread of the observed intensities.

Table 4-3. Data for the calculation of the constants,
A and B, that determine the enhancement factor.

ThIV					ThIII				
	$\frac{I_H}{I_0}$	$\frac{I_H}{I_0} - 1$	$\sqrt{\frac{I_H}{I_0} - 1}$ observed	calculated	$\frac{1}{AP+B}$	$\frac{I_H}{I_0}$	$\frac{I_H}{I_0} - 1$	$\sqrt{\frac{I_H}{I_0} - 1}$ observed	calculated
P (torr)									
0.2	8.7	7.7	2.8	2.8	$\frac{1}{0.2A+B}^*$	5.5	4.5	2.1	2.0
1.0	4.7	3.7	1.9	2.6	$\frac{1}{A+B}$	4.0	3.0	1.7	1.9
5.0	4.4	3.4	1.8	1.9	$\frac{1}{5A+B}$	2.3	1.3	1.1	1.4
10	3.3	2.3	1.5	1.5	$\frac{1}{10A+B}^*$	2.0	1.0	1.0	1.0

The calculated values of A and B are:

For Th IV: $A=0.031$, $B=0.36$

For Th III: $A=0.053$, $B=0.47$

Thus $\frac{B}{A} \approx 10$ for both Th III and Th IV.

Now, considering the case where $P=1$ torr, the following can be written:

$$\frac{N_g \sigma_g}{N_{Th} \sigma_{Th}} = \frac{A}{B} = \frac{1}{10}$$

since $\sigma_{Th} \gg \sigma_g$, ($\sigma_g \approx 10 \sigma_{Th}$ is a reasonable estimate).

$$\therefore N_{Th} \approx N_g$$

$$\text{but } T_{Th} \gg T_g$$

$$\therefore P_{Th} \gg P_g$$

Hence, the pressure in the arc channel is much greater than the gas pressure measured by the vacuum gauge. This probably explains why the observed effect is much less than that forecast in Table 3-1.

It is interesting to note that as P tends to zero the factor $\frac{1}{AP+B}$ tends to $\frac{1}{B}$. This means that a limit can be set to the enhancing effect with respect to the pressure. Actually, this limit was observed during the experiment when the pressure was lowered below 0.2 torr, which is the lowest pressure shown in the data. The curve shown in Fig. 4-3 shows this clearly, where the factor $\frac{1}{AP+B}$ is plotted vs P , using the values for A , B

obtained from the observations (Table 4-4). An important point here is that the upper limit of $\frac{1}{AP+B}$ thus obtained, depends only on $N_{Th}\sigma_{Th}$ and therefore can be used to establish N_{Th} if the total collision X-section σ_{Th} for electrons on thorium atoms is known, since $B=N_{Th}\sigma_{Th}$. Alternatively, if N_{Th} is known then the upper limit on the factor $\frac{1}{AP+B}$ can be used to obtain σ_{Th} . This will depend very much on the accuracy of the experiment, but in principle it can be done.

Another point that can be drawn here is that, since the upper limit of the enhancement factor $\frac{1}{AP+B}$ is $\frac{1}{B}$ or $\frac{1}{N_{Th}\sigma_{Th}}$, therefore the enhancement will be greater for arcs in which N_{Th} is lower, i.e., for lower arc current. This possibly explains why the present data show less enhancement than Klinkenberg found, since higher arc currents have been used here. This indicates that a high degree of enhancement requires a low current, i.e., a faint source, so that this type of arc does not look too promising as a tool for the analysis of atomic spectra by the assignment of lines to their correct ionization stage.

As for the n-dependence of the intensification effect which should lie within the factor $\frac{1}{AP+B}$, it can be seen that

Th IV: A = 0.031 B = 0.36

Th III: A = 0.053 B = 0.47

Table 4-4. Data for obtaining the limiting value of the enhancement factor.

P (torr)	$\frac{1}{AP+B}$		P (torr)	$\frac{1}{AP+B}$	
	Th III	Th IV		Th III	Th IV
0	2.12	2.78	10	1.00	1.49
0.2	2.08	2.70	20	0.65	1.02
0.4	2.04	2.70	30	0.49	0.78
0.8	1.96	2.63	40	0.39	0.63
1.0	1.92	2.56	50	0.32	0.52
1.5	1.81	2.44	75	0.22	0.37
2.0	1.72	2.38	100	0.17	0.29
3.0	1.59	2.22	150	0.12	0.20
4.0	1.47	2.08	200	0.09	0.15
5.0	1.37	1.96	250	0.07	0.12
6.0	1.27	1.82	300	0.06	0.10
7.0	1.19	1.72	350	0.05	0.09
8.0	1.12	1.64	400	0.05	0.08
9.0	1.05	1.56			

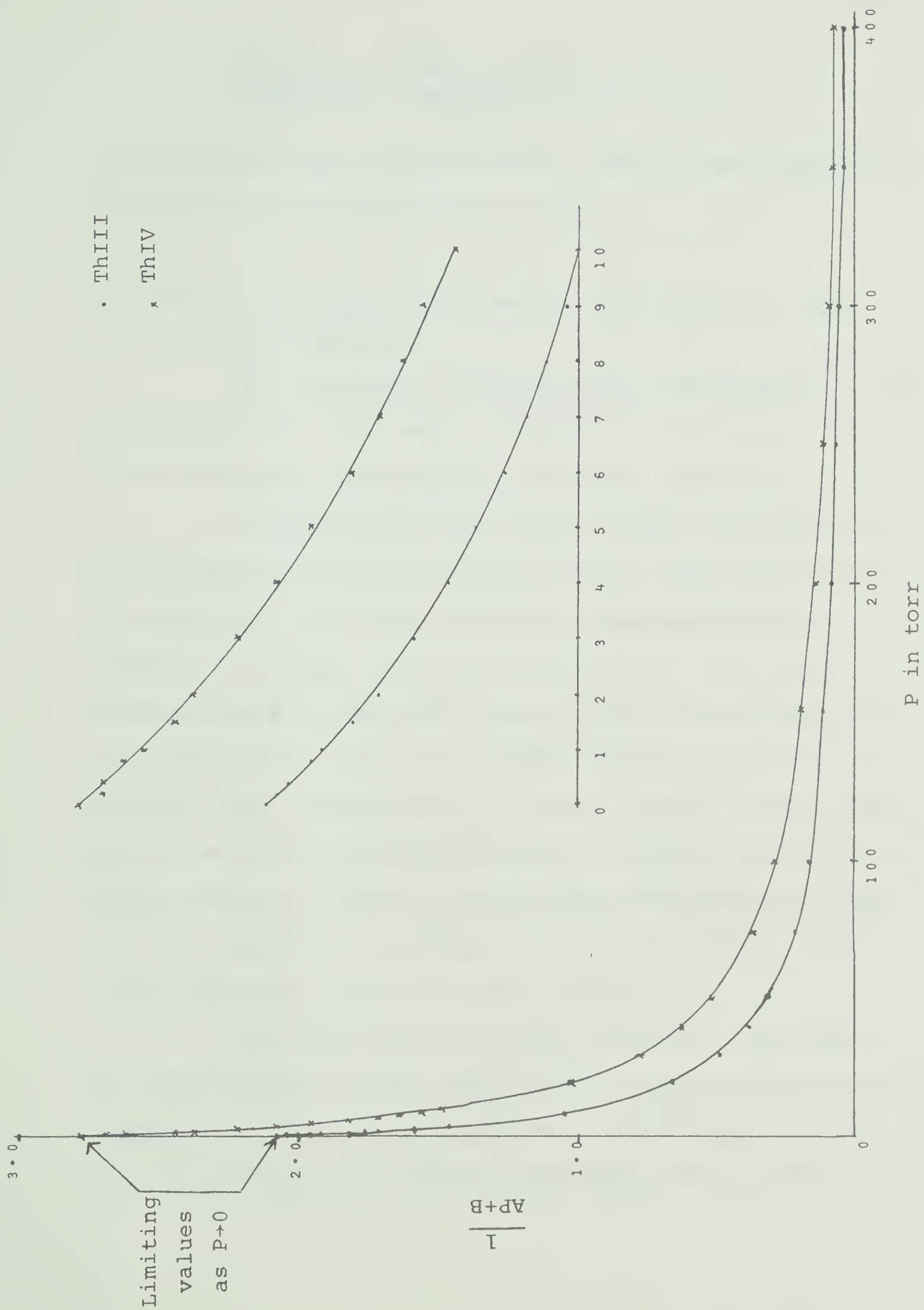


Fig. 4-3. Graphs showing the limiting values of the enhancement factor.

$$\frac{(B)_{\text{Th III}}}{(B)_{\text{Th IV}}} \approx \frac{(A)_{\text{Th III}}}{(A)_{\text{Th IV}}} \approx 1.5 = \frac{3}{2}$$

This suggests that α varies as n^2 . This result agrees well with the curves at $P=5, 10$ torr.

4.3 Error Estimation and Possible Improvement in Experimental Technique.

The tolerance involved in the measurement of the line intensities was well reflected by the large fluctuations obtained on the digital voltmeter readings.

First of all, there was an error introduced by the instability of the magnetic field. This error could be calculated from the calibration curve described in Chapter II. Thus, for a fluctuation of ± 1 mv at the maximum field H , where the slope of the calibration curve is almost flat, the error estimate would be around 0.1%. However, for a fluctuation of ± 1 mv at lower fields, where the slope of the calibration curve is steep, the error might amount to a few %, so that when readings were taken at the lower field, a certain time was allowed to elapse until the field remained almost stable.

The main source of error, however, came from the unsteadiness of the light source. The principal factor contributing to this unsteadiness was the non-uniformity of the surface of the thorium electrode and the way it

was struck by the vibrating tungsten electrode. This, coupled with the easiness at which the oxidized part of the thorium electrode got inflamed, did lead to very high fluctuations in the readings. For these reasons, the various adjustments described earlier had to be made to give a steady length of the positive column. Any estimate of the errors involved from these factors was made from the mean deviation of the statistical fluctuations so produced.

A possible improvement in the experimental technique, aimed at diminishing the high fluctuations observed on the digital voltmeter, would be to use two photomultipliers, one for the lines measured and the other for all the light coming from the source. The signals from both photomultipliers would then be sent through a ratio-amplifier which, if fast enough to respond to the frequency of the fluctuations, should yield a constant ratio, which is the equivalent to the line intensity. This could be achieved by placing a beam-splitter between the quartz lens and the entrance slit of the spectrometer (as described in Chapter II) such that a sufficient fraction of the light coming from the source can be reflected onto the spectrometer entrance slit. The signals, usually, very small, would then be sent through two pre-amplifiers and a ratio-amplifier with a fast response, into the

digital voltmeter. (This technique was attempted in this project, but without obtaining any greater accuracy than was obtained using the one-photomultiplier method, probably because the equipment available was not ideally suited to this particular problem.)

CHAPTER V

SUMMARY

Both qualitative and quantitative investigations have been conducted into enhancement effect of a magnetic field on the ionized spectrum lines of thorium produced in an interrupted vacuum arc, with a view to explain the effect through the phenomenon of ambipolar diffusion.

The qualitative part dealt with the identification of the enhanced ionized lines obtained on photographic plates. The usual spectroscopic methods were adopted for obtaining the spectra. In the quantitative part, some of the selected enhanced lines from different ionization stages, had their intensity measured by means of the photoelectric method.

Theoretical considerations have been introduced, bringing out the relations that the involved parameters should follow if the process responsible for the magnetic enhancement effect did involve ambipolar diffusion. The following experimental results pertaining to the suggested mechanism have been found:

- i) The diffusion of the charged particles across the magnetic field is reduced by

the presence of a magnetic field.

- ii) The effect becomes less important as the pressure is increased.
- iii) The magnitude of the enhancement for pressures of 10 torr or less apparently varies as the inverse square of the magnetic field.
- iv) The effect is more pronounced for more highly-ionized atoms, possibly varying as the square of the charge state of the atom responsible for the particular line.

These results are in general agreement with an enhancement mechanism based on ambipolar diffusion.

The effect of enhancement was observed in all the elements investigated. It appears to be more pronounced in the rare earth, thorium. However, with the other rare earth, hafnium, since it has most of the lines from its trebly-ionized atoms in the ultra violet region, it was not possible to study the effect. Generally, a weak enhancement effect was observed for the lines from doubly-ionized atoms and strong enhancement from the trebly-ionized. Also, evidence of enhancement was found mainly in the lines falling in the shorter wavelength region.

Finally, because of the inevitable fluctuations in the intensity, a fairly bright source was necessary,

which meant a higher electric current. However, it was found from the results obtained in this investigation that at a higher pressure, which is generated by a higher electric current, the enhancement produced is less. It thus appears that this type of light source is not particularly well-suited to separating spectrum lines into their different ionization stages.

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